TESTING AND MODELLING OF SHOCK ABSORBING MATERIALS IN TRANSPORTATION CASKS

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ABSTRACT

Soft Impact Limiters, such as polyurethane foams and aluminum honeycombs are being studied to develop a broad base of information on the mechanical behavior of these materials. Static and dynamic tests under different load configurations were carried out and the results are presented and discussed here. Types of material tested included aluminum honeycombs (hexagonal cell structure) and closed cell rigid polyurethane foams. Four different densities of each material were tested.

INTRODUCTION

The Transportation Base Technology Program at Sandia National Laboratories emphasizes various aspects of technology development for solving waste transportation and packaging problems for the DOE and other organizations (1). The mechanical behavior of aluminum honeycombs and polyurethane foams are currently being studied, results of which are being used for the development of constitutive models, based on the concepts of damage mechanics (2).

The energy absorption process for these materials are strain rate dependent (3-6). Extensive literature is available on the testing and designing with cellular materials (6) but the energy absorption mechanisms especially in the case of large deformations are not understood properly. Obtaining experimental data for different load paths, and the subsequent development of theoretical constitutive models for predicting material behavior is hence essential for developing safe and cost effective methods of design for energy absorbing packaging materials.

MATERIAL SPECIFICATIONS

The materials tested included aluminum honeycombs manufactured by Hexcel Corp (Dublin, CA) and rigid polyurethane foams manufactured by General Plastics (Tacoma, WA) under the brand name LAST-A-FOAM. For both the materials four different densities were tested (49.7(3.1 lb/cu.ft), 129.8 (8.1 lb/cu.ft), 193.9 (12.1 lb/cu.ft) and 354.17 (22.1 lb/cu.ft) Kg/cu.m for honeycombs and 48.1 (3 lb/cu.ft), 80.1 (5 lb/cu.ft), 160.3 (10 lb/cu.ft) and 320.5 (20 lb/cu.ft) Kg/cu.m for foams). The honeycombs were manufactured from 5052 grade aluminum alloy and the honeycombs had an average cell size of 3.175 mm. The 40.1 and 80.1 Kg/cu.m foams were manufactured by a gas blown process whereas the remaining two densities were manufactured by a water blown process.

STATIC TESTS

These series of tests were performed along different load paths using a servo controlled, multiaxial Instron loading frame. Static tests included uniaxial tension and uniaxial compression (7), and tests were carried out as per MIL-STD-401A and ASTM specifications.

Four different densities of honeycombs and foams have been tested in several orientations to understand their anisotropic character. Honeycombs were tested in three different orientations (T, L and W) (6) relative to the cell structure, and foams were tested in two different orientations with respect to the cell formation direction.

The uniaxial compression tests were carried out on a 100,000 lb (445 KN) servo controlled loading frame. The load was monitored by a strain gage type load cell and the displacement monitored by a 10 in (254 mm) LVDT. The corresponding signals were acquired by a Issac 2000 data acquisition system. The test specimens measured 0.1 X 0.1 X 0.1 m and were loaded at a constant rate of 0.95 mm /sec (0.0375 in /sec) for all the tests.

DYNAMIC TESTS

Dynamic tests were carried out at two different strain rates of 1.0 /sec and 100.0 /sec.

Strain Rate of 1.0 /Sec

Tests were carried out using the same facility as the static tests and a sample size of 0.1 X 0.1 X 0.1 m (same as static uniaxial compression) was used. A constant strain rate of 1.0 /sec was maintained during the tests (8).

Strain Rate of 100.0 /Sec

These tests were carried out on a modified and instrumented Charpy impact tester using a specimen size of 0.0254 m (dia) X 0.0254 m (ht) for foams and 0.0254 X 0.0254 X 0.0254 m for the honeycomb specimens (8). Tests carried out on the foams included both unconfined uniaxial and confined compression; the modification for the confined compression tests is shown in Fig. 1. The apparatus consists of a split steel cylinder inside which the specimens are placed, and then confinement pressure is applied with the help of two locknuts. However provisions for measuring the applied confinement pressure were not made in the design.

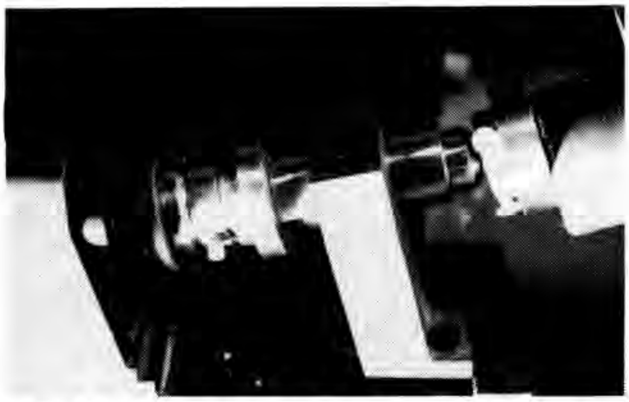

Fig. 1. Setup for confined compression on Charpy.

In addition to the regular uniaxial compression tests on the honeycombs, a few tests were run where the two open ends of the specimen were closed. Thin metal sheets were attached (Fig. 2) by using a high strength epoxy adhesive and the specimens were tested in the T direction (strongest direction) to study the effect of air entrapment in the cell structure. At the end of the test, the specimens were photographed to record the externally visible failure patterns.

A series of drop tests were carried out to study the effect of size on the plateau stress of the materials. The arrangement consists of a 59.3 Kg steel cylinder to one end of which the test specimens are attached. The whole assembly was raised to the required height (as dictated by the strain rate requirements) by a two ton crane and then dropped on to a concrete pad. The load signals for the impact processes were picked up by a transducer (9041 A Kistler load cell) and were acquired by a data acquisition system (8) for analysis.

TEST RESULTS

Aluminum honeycombs exhibit highly anisotropic behavior, the T direction being much stronger than the L and W direction (8). Table I gives a comparison of the plateau stress values for the honeycombs under different loading conditions. In going from the static to the 1.0 /sec strain rate, the results obtained indicate that there is a rate effect, with the exception of the 193.9 Kg/cu.m specimens. The tests performed on the Charpy at an average strain rate of 100.0 /sec show a reduction of plateau stress. Although the strain rate has increased, the specimen size is considerably smaller and what we are observing in this case is possibly the effect of specimen size. Reduction in size has resulted in the reduction of plateau stress.

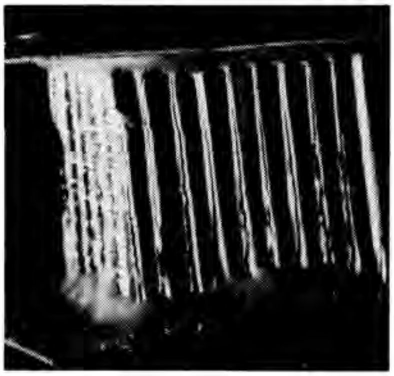

Fig. 2. Honeycomb specimens with ends closed.

Drop tests performed at an average strain rate of approximately 100.0 /sec, showed an increase in the plateau stress values for all the three densities that were tested. The sample size for the drop tests were much larger than those tested on Charpy. Strain rate having remained the same in both the cases, the increase in plateau stress can be explained by the effect of specimen size. Larger size specimens give larger strength.

It is however worth noticing that in going from a strain rate of 1.0 /sec to 100.0 /sec, the stress strain behavior of the material has changed significantly for the 354.15 Kg/cu.m specimens. Although there has not been an increase in the peak stress in the latter case, the load drops quite sharply as shown in Fig. 3. In contrast, this drop is more gradual for the slower strain rates. The reason for this is not very clear at this stage, and it is possible that air entrapment might have something to do with it. It is also possible that the first stress wave propagating through the specimen weakens the specimen, leaving behind a degraded specimen for the subsequent loading phase (4).

Closing the open ends of the cells tend to reduce the lockup strain quite significantly in all the cases as is evident from Table II. For the 354.15 Kg/cu.m specimens the peak load drops quite sharply and then rises again quite rapidly at first, followed by a more gradual increase up to lock up. Visual inspection of the specimens with closed ends indicate that there might be a different failure mechanism. For open ended specimens normal failure starts with the formation of plastic hinges, followed by local buckling of the cell walls and it moves from one end to the other like a moving front. For higher densities this local buckling process is supplemented by tensile splitting as a result of adhesive failure.

In contrast the specimens whose ends were closed seem to be developing a plane of plastic hinges at some intermediate point (Fig. 4 (a) and (b)), and the top and lower half of the specimen slides with respect to this plane as the buckling progresses into the two halves.

Polyurethane foams also exhibit anisotropy, the direction perpendicular to cell growth being stronger. However the effect of anisotropy on material properties is not too pronounced. The comparison of plateau stress values given in Table III shows that the foams do show rate effect, and similar

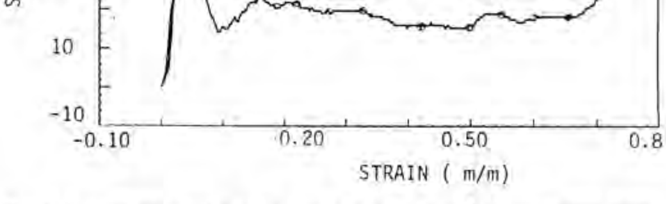

Fig. 3. Stress vs strain plot for 354.17 Kg/m^3 Aluminum honeycomb under different loading conditions

TABLE I

Comparison of Plateau Stress Values for Aluminium Honeycombs Under Different Loading Conditions

(Kg/m^3) Density	(MPa) Static (Instron)	(MPa) 1.0/sec (Instron)	(MPa) 100.0/sec (Charpy)	(MPa) Ends plugged (100.0/sec)	(MPa) Drop test
49.7(T)	0.9	1.07	0.9	0.9	1.10
129.8(T)	4.41	5.17	4.41	4.14	4.90
193.9(T)	10.34	10.34	13.80	9.66	17.24
354.2(T)	25.52	29.66	20.69	-	-

TABLE II

Comparison of Lockup Strains for Aluminium Honeycombs

Density (Kg/m^3)	Static (%)	1.0/sec (%)	100.0/sec (%)	Ends plugged (%)
49.7 (T)	80	75	89	52
129.8(T)	73	70	73	52
193.9(T)	79	74.5	74	60
354.2(T)	78	66.5	72	-

increases have been reported in literature before. At a strain rate of 1.0 /sec all densities show an increase in plateau stress over their corresponding static values.

It is however observed that in going from the 1.0 /sec to the 100.0 /sec strain rate tests on the Charpy, there is slight or no increase for the lower density foams; but the increase in plateau stresses for the two higher density specimens are substantial. This can be explained partly by rate effect and partly by size effect. The higher density foams have been observed to be quite brittle (they exhibit extensive tensile splitting) and for brittle materials larger sizes tend to produce lower strength. The lower density specimens are less brittle than those of the higher density. The lower density specimens showed little or no increase in plateau stress in the Charpy tests. Positive rate effect in conjunction with a negative size effect might explain this behavior of the lower density foams.

In the drop test with the exception of the 48.1 Kg/cu.m samples all other densities exhibited varying degrees of rupture and splitting (Fig. 5 (a), (b)) which explains the lower plateau stresses obtained for these densities. The 48.1 Kg /cu.m samples registered an increase in plateau stress values, suggesting that for this density strength increases with increasing size. This is possible, since the specimens of the above density do not exhibit brittle behavior (tensile splitting was not observed). Visual inspection of drop test specimens at the end of the test, seems to indicate that the specimens had been subjected to the combined effect of shear and compressive stresses.

Results from confined compression tests show, that confinement reduces the plateau stress except in case of the 320.5 Kg/cu.m specimen which exhibits extensive splitting in uniaxial compression. Confinement prevented the splintering of the specimen, allowing a higher plateau stress to be achieved. As can be seen from Table IV decrease in lockup strains are observed for all the four densities. Triaxial state of loading has been observed to produce a significant reduction in the plateau stress level and data indicates that with the increase in confinement pressure plateau stress decreases. Data from the dynamic confined compression and triaxial compression both corroborate the fact that confinement causes a reduction in plateau stress.

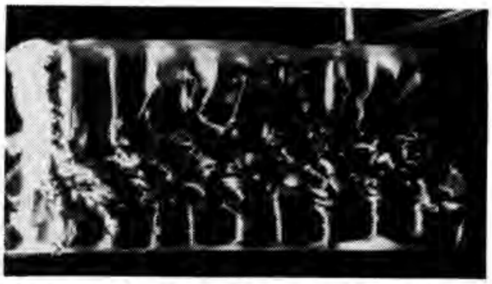

Fig. 4. (a) Crushed closed end honeycomb specimen (129.8 Kg/m^3)

Fig. 4. (b) Crushed closed end honeycomb specimen (193.9 Kg/m^3).

DISCUSSIONS

Results from tests carried out here indicate that both aluminum honeycombs and rigid polyurethane foams exhibit rate and size effect and this needs to be considered in the

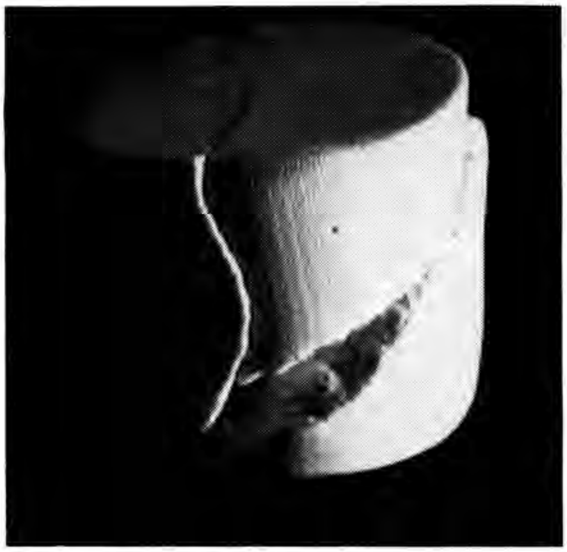

Fig. 5. (a) 160.3 Kg/m^3 foam drop test specimen.

Fig. 5. (b) Splintered 320.5 Kg/m^{-3} foam drop test specimen.

design and development process of impact limiters. The ability to understand and predict the behavior of these materials under different load paths is critical, since in reality the packaging would be subjected to a complex dynamic loading pattern. Development of impact limiters is a very costly process involving testing of scale models, based on which subsequent modifications are made (9, 10). Analytical methods in conjunction with engineering test results have been used to predict impact limiter load deflection curves (11), but these codes do not include any constitutive model, and are empirical in nature. Construction of energy absorption curves (12) for these materials can often be quite useful in deciding the type of material and the volume required for a particular situation.

These energy absorption curves are plots of specific energy absorption versus stress thus giving the specific energy absorption capacity for a given stress. If the limiting value of the stress that can be transmitted is known, then the materials that can be used for the design can be obtained from the envelope of the energy absorption curves. A energy absorption curve constructed for aluminum honeycombs at a strain rate of 100.0 /sec is shown in Fig. 6.

CONCLUSIONS

The mechanical behavior of cellular foams and honeycombs for some stress paths were recorded. These materials behave differently under different strain rate, specimen size and confinement conditions. The resulting differences in their energy absorption capacity must be considered in a design procedure. Energy absorption curves for different loading conditions should be constructed to aid in the design process. While some of the experimental results reported out here could be explained from the physiological phenomenon

TABLE III

Comparison of Plateau Stress Values for Compression of Polyurethane Foams

Density (Kg/m^3)	Static (MPa)	1.0/sec (Mpa)	100.0/sec (Mpa)	Confined Compression (Mpa)	Drop Test (Mpa)	Triaxial (MPa)
48.1	0.38	0.48	0.48	0.34	0.55	0.19 (*0.17)
80.1	0.86	1.03	1.10	0.97	1.07	0.5 (*0.52)
160.3	2.21	2.41	3.31	2.76	2.76	1.38 (*0.69)
320.5	6.90	8.69	10.34	12.41	8.97	6.55 (*1.03)

(*) Confinement pressure in Mpa.

TABLE IV

Comparison of Lockup Strains for Polyurethane Foams

Density (Kg/m^3)	Static (Instron) (%)	1.0/sec (Instron) (%)	100.0/sec (Charpy) (%)	Confined Compression (Charpy) (%)
48.1 (/)	78	80	75	70
48.1 (//)	80	70	75	60
80.1 (/)	70	74	75	50
80.1 (//)	70	74	75	48
160.3 (/)	60	67.5	68	45
160.3 (//)	60	60	60	45
320.5 (/)	33	30	-	28
320.5 (//)	35	30	-	28

(/) Loading perpendicular to formation direction.
(//) Loading parallel to formation direction.

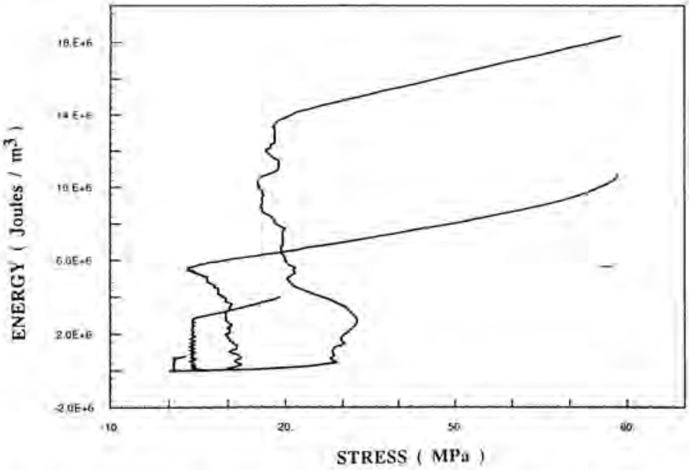

Fig. 6. Energy plot for 49.7, 129.8, 193.9 and 354.17 Kg/m^3 aluminum honeycombs (Strain rate 100./sec).

associated with their crushing, further studies are necessary for improving our understanding of these effects. The results from these tests are currently being used for developing constitutive models for Impact Limiter materials (13).

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